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# Ultrashort Pulse Delivery in Hollow-Core Photonic Bandgap Fiber at 540 nm

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**Abstract:** We report the transmission and compression of ultrashort pulses with a wavelength of 540 nm in hollow-core photonic bandgap fiber. We have observed pulses as short as 115 fs after 1 m of fiber.

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Hollow-core photonic bandgap fibers (HC-PBGFs) are ideally suited to the transmission of high-intensity ultrafast laser pulses for two reasons. Firstly the photonic bandgap cladding confines the majority of the guided mode in the air-filled core, reducing the Kerr nonlinear response of the structure by approximately three orders of magnitude relative to solid-core fibers. Hence the effects of self-phase modulation and Raman scattering are greatly reduced, allowing high-intensity pulses to propagate without catastrophic distortion. Secondly, material dispersion has a negligible effect in the dispersion of the guided mode. Instead, dispersion is dominated by bandgap and waveguide dispersion, which are set by the size and shape of the cladding and core. Therefore by scaling the size of the structure the dispersion curve can be shifted to different wavelengths.

We have fabricated HC-PBGFs to guide light in the range 500-600 nm. We have used fibers in which the zero dispersion wavelength (ZDW) is shorter than the input wavelength so that the pulses propagate in the anomalous dispersion regime. By coupling sufficient pulse energy into these fibers we have observed soliton dynamics and pulse compression at a much shorter wavelength than previous investigations in HC-PBGF [1, 2, 3].

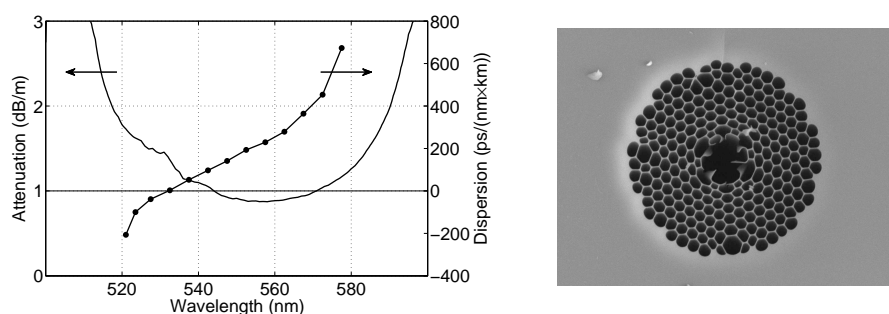


Fig. 1. Measured dispersion of HC-PBGF2 and electron micrograph of the cleaved end face. The damage around the hollow core was caused during the fiber end face preparation.

In order to generate ultrashort pulses at 539 nm we used a 10 W, 20 MHz amplified modelocked fiber laser (from Fianium Ltd.) emitting at a wavelength of 1064 nm. The 8 ps, 12 nm pulses, highly chirped due to self-phase modulation in the amplifier, were compressed in 15 m of seven-cell HC-PBGF [4]. The combined loss of coupling and transmission in the fiber was approximately 50% and the fraction of the pulse energy traveling as a dispersive wave was removed with a long-pass filter. At the output, we obtained transform-limited pulses centered at 1078 nm (due to soliton self-frequency shift in the hollow-core fiber) with a duration of 300 fs and pulse energy of 100 nJ. This was frequency doubled in a 3 mm long noncritically-phasematched LBO crystal. The short pulse duration and high peak power allowed second harmonic generation with greater than 50% efficiency, yielding 55 nJ pulses at 539.0 nm with a FWHM duration of 300 fs, a bandwidth of 1.5 nm, and an average power of 1.1 W.

In two separate experiments, these pulses were coupled into two different sections of seven cell HC-PBGF designed to operate around 540 nm. The first had a bandgap stretching from 496 to 555 nm and a ZDW of approximately 510 nm (HC-PBGF1, 1.3  $\mu\text{m}$  pitch, 5.4  $\mu\text{m}$  core diameter). The second had a bandgap of 532–583 nm and zero dispersion of 532 nm (HC-PBGF2, 1.5  $\mu\text{m}$  pitch, 5.6  $\mu\text{m}$  core diameter), with the dispersion curve shown in Fig. 1. Both had a loss of approximately 1 dB/m.

After propagating through 1.35 m of HC-PBGF1, the pulse duration was measured with an intensity autocorrelator (APE PulseCheck). We observed that the pulse duration decreased as the output power was increased, becoming approximately equal to the input pulse duration at an average output power of 385 mW. At this point the effect of self-phase modulation became strong enough to balance the anomalous dispersion of the fiber and the pulse propagated as a fundamental soliton. The central wavelength of the output spectrum at this power level was 540.8 nm; hence the self-frequency shift relative to the input was 1.8 nm.

Much more dramatic effects were seen in a 1 m length of HC-PBGF2 due to the proximity of its ZDW to the pump wavelength. The data for this fiber is shown in Fig. 2. Even at the lowest measurable power, the output pulses were shorter than the input (250 fs duration for 100 mW output power). As the pulse energy was increased we observed compression of the output by almost a factor of three relative to the input (the minimum measured pulse duration was 115 fs at an output power of 670 mW), along with a commensurate increase in the spectral bandwidth to 2.8 nm. This yielded a time-bandwidth product of 0.33. The central wavelength of the pulses lengthened to 541.4 nm, a shift of 2.4 nm. The soliton length was 3 m and the soliton number approximately 2.5 for a power of 670 mW.

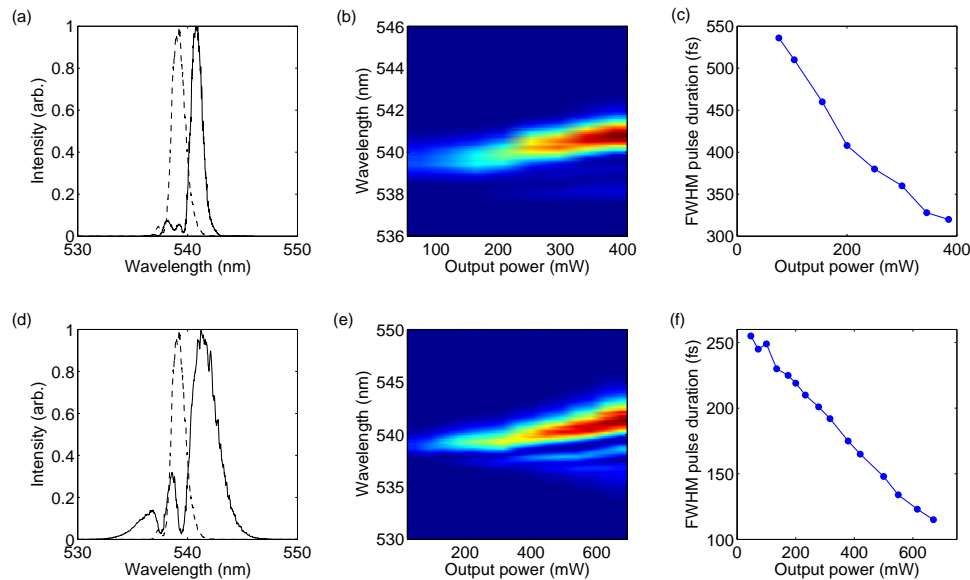


Fig. 2. Results for for HC-PBGF1 (a-c) and HC-PBGF2 (d-f). (a,d) Input spectrum (dashed line) and output spectrum at maximum power (solid line), (b,e) evolution of linearly scaled output spectrum as a function of power, (c,f) output pulse duration as a function of power.

In conclusion, we present the first demonstration of soliton propagation and compression at 540 nm in HC-PBGF. This is an important wavelength range in which many pulsed laser sources exist but where delivery fibers have not previously been available. This study paves the way for fiber-based ultrashort pulse delivery over meter length-scales for a range of imaging, processing, and diagnostic applications requiring visible light.

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